An introduction to FLUKA physics models and applications

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Topics

- Hadronic interactions in **FLUKA**: short description and examples
- Neutrino interactions
- Photonuclear reactions
- *(Ionization Energy losses, multiple scattering, EM showers, muons)*
- Complex benchmarks
- The atmospheric neutrino calculations and other “cosmic ray” applications
- Heavy ion interactions: work in progress
FLUKA: generalities

FLUKA

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Interaction and transport MonteCarlo code

- Hadron-hadron and hadron-nucleus interactions 0-100 TeV
- Nucleus-nucleus interactions 0-10000 TeV/n: under development
- Electromagnetic and $\mu$ interactions 1 keV-100 TeV
- Neutrino interactions
- Charged particle transport including all relevant processes
- Transport in magnetic field
- Combinatorial (boolean) geometry
- Neutron multigroup transport and interactions 0-20 MeV
- Analogue or variance reduction calculations
A multipurpose code

The program can be used in different fields such as shielding, dosimetry, high energy experimental physics and engineering, cosmic ray studies, medical physics, etc.

- Each radiation component is treated as far as possible with the same level of accuracy (it's like having 4 different programs in one, for pure neutron, electron-photon or muon problems – and hadrons, of course!)

- FLUKA can be run in fully analog mode, for calorimetry. It can calculate coincidences and anticoincidences

- It can also be run in biased mode, for shielding design

But also experimental high energy physicists need sometimes to make studies of deep penetration or rare events: hadron punchthrough, radiation background in underground experiments, muon production over short decay lengths
**FLUKA History**

- **Beginning of the FLUKA history**: 1962 Johannes Ranft (Leipzig) and H. Geibel (CERN): MonteCarlo for high energy beams
- **The name FLUKA**: 1970: calorimeter fluctuations on an event-by-event basis (FLUKA = FLUktuierende KAskade).
- **From the beginning of the 70’s**: J. Ranft and coworkers (Leipzig), with contributors from Helsinki (J. Routti, P. Aarnio) and CERN (G.R. Stevenson, A. Fassò) till ≈ 1987.
- **The present code**: since 1990 mostly INFN-Milan: little or no remnants of older versions. Link with the past: J. Ranft, A. Fassò
- **The GEANT-FLUKA interface**: 1993 the FLUKA hadronic package interfaced with GEANT3. no development/update thereafter
- **In MCNPX**: High energy hadronic FLUKA generator, 1990 status
- **The FLUKA project**: since Sept. 2001 FLUKA is an official INFN project
The FLUKA hadronic models

**Hadron-Nucleon**
- Elastic, exchange
- Phase shifts, data, eikonal
- P < 3-5 GeV/c
- Resonance production and decay
- Low E $\pi, K$
- Special
- High Energy
- DPM hadronization

**Hadron-Nucleus**
- P < 4-5 GeV/c
- PEANUT: Sophisticated GINC preequilibrium
- High Energy Glauber-Gribov multiple interactions
- Coarser GINC
- Evaporation/Fission/Fermi break-up
- $\gamma$ deexcitation
Hadron-nucleon interaction models

Elastic, charge exchange and strangeness exchange reactions:

- Available phase-shift analysis and/or fits of experimental differential data
- At high energies, standard eikonal approximations are used

Particle production interactions: two kind of models

- Those based on “resonance” production and decays, which cover the energy range up to 3–5 GeV
- Those based on quark/parton string models, which provide reliable results up to several tens of TeV
Nucleon–nucleon cross sections I

Total and elastic cross section for p–p and p–n scattering, together with experimental data (left), isospin decomposition in the $T=0$ and $T=1$ components (right)
π–nucleon cross sections I

Elastic, chx and inel. cross sections for π–N scattering (left), isospin decomposition in the T=1/2 and T=3/2 components (right)
Nonelastic hN interactions at intermediate energies

- $N_1 + N_2 \rightarrow N'_1 + N'_2 + \pi$ threshold around 290 MeV, important above 700 MeV,
- $\pi + N \rightarrow \pi' + \pi'' + N'$ opens at 170 MeV.

Dominance of the $\Delta$ resonance and of the $N^*$ resonances $\rightarrow$ reactions treated in the framework of the isobar model $\rightarrow$ all reactions proceed through an intermediate state containing at least one resonance.

\[
N_1 + N_2 \rightarrow N'_1 + \Delta(1232) \rightarrow N'_1 + N'_2 + \pi \\
\pi + N \rightarrow \Delta(1600) \rightarrow \pi' + \Delta(1232) \rightarrow \pi' + \pi'' + N' \\
N_1 + N_2 \rightarrow \Delta_1(1232) + \Delta_2(1232) \rightarrow N'_1 + \pi_1 + N'_2 + \pi_2
\]

Resonance energies, widths, cross sections, branching ratios from data and conservation laws, whenever possible. Inferred from inclusive cross sections when needed.
Inelastic hN at high energies: (DPM, QGSM, ...)

- Problem: “soft” interactions $\rightarrow$ no perturbation theory.
- Solution: Interacting strings (quarks held together by the gluon-gluon interaction into the form of a string)
- Interactions treated in the Reggeon-Pomeron framework
- At sufficiently high energies the leading term corresponds to a Pomeron ($IP$) exchange (a closed string exchange)
- Each colliding hadron splits into two colored partons $\rightarrow$ combination into two color neutral chains $\rightarrow$ two back-to-back jets
- Physical particle exchange produce single chains at low energies
- Higher order contributions with multi-Pomeron exchanges important at $E_{lab} \geq 1$ TeV
From resonance production to DPM

Single chain diagram for $\pi^+ - p$ scattering, corresponding to a physical particle exchange. The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities.

Leading two-chain diagram in DPM for $p - p$ scattering. The color (red, blue, and green) and quark combination shown in the figure is just one of the allowed possibilities.
DPM: chain examples

Leading two-chain diagrams in DPM for $p - p$ (left) and $\pi - p$ (right) scattering. The color (red, blue, and green) and quark combinations shown in the figure are just one of the allowed possibilities.
DPM and hadronization

from DPM:

- Number of chains
- Chain composition
- Chain energies and momenta
- Diffractive events

Almost No Freedom

Chain hadronization

- Assumes chain universality
- Fragmentation functions from hard processes and $e^+e^-$
- Transverse momentum from uncertainty considerations
- Mass effects at low energies

The same functions and (few) parameters for all reactions and energies
Nonelastic hN at high E :($\pi^+$ p), 7-22 GeV

Invariant cross section spectra, as a function of Feynman $x_F$ of negative (left), and positive (right) pions emitted for $\pi^+$ on protons at various momenta. Data from M.E Law et al. LBL80 (1972).
Nonelastic hN high E: \((K^-p)\), \((\pi^-p)\) 10-16 GeV, \(p_T\)

Double differential cross section for \(K^-p \rightarrow \Lambda X\) at 10 GeV/c (left), \(p_T\) spectra of \(\pi^+\) and \(\pi^-\) produced by 16 GeV/c \(\pi^-\) incident on an hydrogen target. Data from M.E Law et al. LBL80 (1972).
Feynman $x_F^*$ (left) and $p_t$ (right) spectra of positive particles and $\pi^-$ produced by 250 GeV/c $\pi^+$ incident on a hydrogen target. Exp. data (symbols) have been taken from M. Adamus et al. ZPC39, 311 (1988).
Elastic, Quasi-elastic and Absorption hA cross sections derived from Free hadron-Nucleon cross section + Nuclear ground state ONLY. Inelastic interaction $\equiv$ multiple interaction with $\nu$ target nucleons, with binomial distribution:

$$P_{r, \nu}(b) \equiv \binom{A}{\nu} P_r^\nu(b) [1 - P_r(b)]^{A-\nu}$$

where $P_r(b) \equiv \sigma_{hN_r} T_r(b)$, and $T_r(b)$ = folding of nuclear density and scattering profiles along the path.

On average:

$$\langle \nu \rangle = \frac{Z \sigma_{hp_r} + N \sigma_{hn_r}}{\sigma_{hA\,abs}}$$

$$\sigma_{hA\,abs}(s) = \int d^2b \left[ 1 - (1 - \sigma_{hN_r}(s) T_r(b))^A \right]$$
h-A at high energies: Glauber-Gribov

One of the possibilities for Glauber-Gribov scattering with 4 collisions

Gribov

\[ \downarrow \]

\[ 2\nu \] chains

2 valence-valence chains

\[ 2(\nu - 1) \] chains between projectile sea and target valence (di)quarks.

No freedom, except in mass effects at low energies.

Fermi motion included \( \rightarrow \) smearing of E and \( p_T \) distributions
Nonelastic hA interactions at high energies: examples

Rapidity distribution of charged particles produced in 200 GeV proton collisions on Hydrogen, Argon, and Xenon target (left) and ratio of rapidity distribution of charged, positive, and negative particles produced in 200 GeV proton collisions on Xenon and Hydrogen (right). Data from C. De Marzo et al., PRD26, 1019 (1982).
Nonelastic hA interactions at high energies: examples

Multiplicity distribution of negative shower particles for 250 GeV/c K⁺ on Aluminium and Gold targets (left), and rapidity distribution of positive, negative, and “π⁺” particle for 250 GeV/c π⁺ on Aluminium (right). Data from I.V. Ajinenko et al. ZPC42 377 (1989) and N.M. Agababyan et al. ZPC50 361 (1991).
Recent improvements in the high energy model

The DPM + Glauber model embedded into old FLUKA versions (and in MCNPx, GEANT-FLUKA) had important limitations:

- Glauber cascade described at an elementary level;
- all resonances assumed on mass shell;
- coarse chain hadronization, and no particular attention to threshold and finite mass effects;
- isospin conservation not enforced at each individual hadron production step;
- transverse motion reasonable but still far from satisfactory;
- simplified description of diffractive processes.
Recent improvements in the high energy model

All improved along the years:
Very old reference: FLUKA92 and GEANT-FLUKA
Many versions in between: most already done in 1995
Latest optimization: chain hadronization \(^1\)

- Threshold and finite mass effects checked against low energy data (chains with few had.)
- Fragmentation functions checked vs. 16-450 GeV h-N and h-A data
- Constraint: hadron multiplicity at 200 GeV
- Balanced optimization: better SPY agreement could be achieved, spoiling low energy data

\(^1\)(G. Collazuol, A. Ferrari, A. Guglielmi and P.R. Sala, NIM A 449 (2000), 609)
Improvements: SPY II: forward yield

π⁻ and K⁻

\( d^2N / (dp/p \, d\Omega) \)

100 mm Be target,
\( \theta \leq 0.2 \) mrad

SPY \( (P \leq 135 \) GeV/c, ⬤) and Atherton et al. \( (P \geq 67.5 \) GeV/c, ⬤)

compared with the

\textit{FLUKA} and the

\textit{GEANT-FLUKA} predictions.
Comparison with SPY I

Double differential cross section for $\pi^+$ (left) and $\pi^-$ (right) production for 450 GeV/c protons on a 10 cm thick Be target (data from H.W. Atherton CERN 80–07, G. Ambrosini et al. PL B425 208 (1998)).
Nonelastic hA interactions at high energies: examples IV

Invariant cross section distribution for $\pi^+$, 24 GeV/c protons on Be (T.Eichten et al. NPB 44, 333 (1972)).

$p_T$ spectra of $\pi^+$ and $\pi^-$ produced by 16 GeV/c $\pi^-$ on H. (M.E Law et al. LBL80 (1972)).
### Improvements: effect on WANF

*Intensity, mean energy and relative abundances for $\nu$ fluxes at NOMAD fiducial area as calculated with the FLUKA and GEANT-FLUKA generator.*

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<td>$\bar{\nu}_e$</td>
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400 GeV/c protons, double fast extraction, $5 \times 10^{13}$ protons every 6 s
Thin graphite target ($\varnothing 5/4$ mm, 13 bars 100 mm each )
Two magnetic lenses focalize 35 and 50 GeV positive
1 Km decay tube
730 Km to Gran Sasso
CERN Neutrino to GranSasso

Nice agreement with experiment $\rightarrow$ confidence in prediction for CNGS
Baseline CNGS target: 13 Graphite rods, \( \varnothing=5(\times 2) 4(\times 11) \) mm, total length 2000 mm, Carbon length 1280 mm

Energy deposition in the standard CNGS target, in GeV/cm\(^3\)/primary, for a 400 GeV proton beam with \( \sigma=0.53\) mm
(Generalized) IntraNuclear Cascade basic assumptions

1. Primary and secondary particles moving in the nuclear medium
2. Target nucleons motion and nuclear well according to the Fermi gas model
3. Interaction probability from $\sigma_{\text{free}} + \text{Fermi motion} \times \rho(r) + \text{exceptions (ex. } \pi\text{)}$
4. Glauber cascade at high energies
5. Classical trajectories (+) nuclear mean potential (resonant for $\pi$’s!!)
6. Curvature from nuclear potential $\rightarrow$ refraction and reflection.
7. Interactions are incoherent and uncorrelated
8. Interactions in projectile–target nucleon CMS $\rightarrow$ Lorentz boosts
9. Multibody absorption for $\pi, \mu^-, K^-$
10. Quantum effects (Pauli, formation zone, correlations…)
11. Exact conservation of energy, momenta and all additive quantum numbers, including nuclear recoil
Formation Zone

Naively: “materialization” time. Qualitative estimate: in the frame where $p_{||} = 0$

$$\bar{t} = \Delta t \approx \frac{\hat{n}}{E_T} = \frac{\hat{n}}{\sqrt{p_T^2 + M^2}}$$

particle proper time

$$\tau = \frac{M}{E_T} \bar{t} = \frac{\hat{n} M}{p_T^2 + M^2}$$

Going to lab system

$$t_{lab} = \frac{E_{lab}}{E_T} \bar{t} = \frac{E_{lab}}{M} \tau = \frac{\hat{n} E_{lab}}{p_T^2 + M^2}$$

As a function of particle rapidity $y$

$$t_{lab} = \bar{t} \cosh y = \frac{\hat{n}}{\sqrt{p_T^2 + M^2}} \cosh y$$

Condition for possible reinteraction inside a nucleus:

$$\nu \cdot t_{lab} \leq R_A \approx r_0 A^{1/3}$$
h-A at high energies: the invariance of the target fragmentation region

The Glauber cascade and the formation zone act together in reaching a regime where the “slow” part of the interaction is almost independent of the particle energy.

This regime can be easily verified looking at charged particle average multiplicities and multiplicity distributions as a function of energy.

- “Fast” tracks, coming from the projectile primary interactions, show the typical $\approx$ logarithmic increase observed for hN interactions.
- “Gray” tracks, mostly due to intranuclear cascade reinteractions tend to saturate just above 10 GeV.
- “Black” tracks, mostly due to evaporation charged particles saturate as well.
Nonelastic hA interactions at high energies: examples

Shower, grey, and black tracks multiplicities for π⁻ (left) and protons (right) incident on emulsion, as a function of the projectile momentum. Open symbols are experimental data from various sources, full symbols are FLUKA results.
Nonelastic hA interactions at high energies: examples II

Correlation between the number of heavy prongs and fast particle multiplicity for protons on emulsion at various momenta, and mutual correlations (\( <n_g> vs n_b\) and \( <n_b> vs n_g\)) between black and grey charged tracks for 400 GeV/c p on emulsion. Open symbols are experimental data from various sources, full symbols are FLUKA results.
“Coherence length”

Coherence length $\equiv$ formation time for elastic or quasielastic interactions.

Given a two body interaction between with four-momentum transfer

$$q = p_{1i} - p_{1f}$$

the energy transfer seen in a frame where the particle 2 is at rest is given by

$$\Delta E_2 = \nu_2 = \frac{q \cdot p_{2i}}{m_2}$$

From the uncertainty principle this $\Delta E$ corresponds to a indetermination in proper time given by $\Delta \tau \cdot \Delta E_2 = \hat{\kappa}$, that boosted to the lab frames gives a coherence length

$$\Delta x_{lab} = \frac{p_{2lab}}{m_2} \cdot \Delta \tau = \frac{p_{2lab}}{m_2} \frac{\hat{\kappa}}{\nu_2}$$

And analogue for particle 1

Can be applied also to $\nu - \hbar$ interactions
Nucleon Fermi Motion

*Fermi gas model:* Nucleons = Non-interacting Constrained Fermions

Momentum distribution \( \propto \frac{dN}{dk} = \frac{|k|^2}{2\pi^2} \)

for \( k \) up to a (local) Fermi momentum \( k_F(r) \) given by

\[
k_F(r) = \left[ 3\pi^2 \rho_N(r) \right]^{\frac{1}{3}}, \quad \rho_N = \text{neutron or proton density}
\]

The Fermi energy \( (k_F \approx 1.36 \text{ fm}, \ E_F \approx 260 \text{ MeV at nuclear max. density}) \) is customarily used in building a soft-consistent Nuclear Potential

\[
\downarrow
\]

Depth of the potential well \( \equiv \) Fermi Energy + Nucleon binding Energy

*Effect on hadron-nucleon interactions*

Smearing of momentum distributions

Smearing of the center of mass energy

Origin of the residual nuclear excitation
Positive Kaons: A probe of Fermi distribution

\[ K^+ \quad K^0 \]

No low mass S=1 baryons → weak \( K^+ N \) interaction
only elastic and ch. exch. up to \( \approx 800 \text{ MeV/c} \)

\((K^+, K^{+'})\) on Pb vs residual excitation, 705 MeV/c, at \(24^\circ\) and \(43^\circ\).

On free nucleon: recoil energy:
43 MeV at \(24^\circ\), 117 MeV at \(43^\circ\).
Pions: nuclear medium effects

Pion-nucleon interactions: non-resonant channel and p-wave resonant formation of $\Delta$'s. In nuclear medium $\Delta$'s can either decay, resulting in elastic scattering or charge exchange, or interact with other nucleons, resulting in pion absorption $\rightarrow$ the width of the resonance is thus different from the free one and the free pion-nucleon cross section must be modified according to

Assuming a Breit-Wigner for the free resonant cross section with width $\Gamma_F$

$$\sigma_{res}^{Free} = \frac{8\pi}{p_{cm}^2} \frac{M_{\Delta}^2 \Gamma_F(p_{cm})^2}{(s - M_{\Delta}^2)^2 + M_{\Delta}^2 \Gamma_F(p_{cm})^2}$$

An “in medium” resonant cross section $\sigma_{res}^A$ can be obtained adding to $\Gamma_F$ the imaginary part of the (extra) width arising from nuclear medium effects:

$$\frac{1}{2} \Gamma_T = \frac{1}{2} \Gamma_F - \text{Im}\Sigma_{\Delta}, \quad \Sigma_{\Delta} = \Sigma_{qe} + \Sigma_2 + \Sigma_3$$

($\Sigma_{qe}, \Sigma_2, \Sigma_3 =$ widths for quasielastic scattering, two and three body absorption)

The effective in-nucleus cross section is then obtained taking also into account a further two-body s-wave absorption cross section derived from the optical model

$$\sigma_t^A = \sigma_{res}^A + \sigma_t^{Free} - \sigma_{res}^{Free} + \sigma_s^A, \quad \sigma_s^A(\omega) = \frac{4\pi}{p}(1 + \frac{\omega}{2m})\text{Im}B_0(\omega)\rho$$
Microscopic pion absorption cross sections

Charged pion absorption cross section for infinite symmetric nuclear matter at two different density values ($\lambda_{abs}^{-1} = \sigma_{abs} \cdot \frac{1}{2} \rho = \sigma_{abs} \cdot \rho_{pro} = \sigma_{abs} \cdot \rho_{neu}$)
**Pions: optical potential**

For pions, a complex nuclear potential can be defined out of the pion-nucleon scattering amplitude to be used in conjunction with the Klein-Gordon equation:

\[
[(\omega - V_c)^2 - 2\omega U_{opt} - K^2] \Psi = m^2_\pi \Psi
\]

In coordinate space, this is written as (the upper/lower signs refer to $\pi^+ / \pi^-$):

\[
2\omega U_{opt}(\omega, r) = -\beta(\omega, r) + \frac{\omega}{2M} \nabla^2 \alpha(\omega, r) - \nabla \cdot \frac{\alpha}{1 + g\alpha(\omega, r)} \nabla
\]

\[
\beta = 4\pi \left[ \left( 1 + \frac{\omega}{M} \right) \left( b_0(\omega) \mp b_1(\omega) \frac{N - Z}{A} \right) \rho(r) + \left( 1 + \frac{\omega}{2M} \right) B_0(\omega) \rho^2(r) \right]
\]

\[
\alpha = 4\pi \left[ \frac{1}{1 + \frac{\omega}{M}} \left( c_0(\omega) \mp c_1(\omega) \frac{N - Z}{A} \right) \rho(r) + \frac{1}{1 + \frac{\omega}{2M}} C_0(\omega) \rho^2(r) \right]
\]

Using standard methods to get rid of the non-locality, in momentum space

\[
2\omega U_{opt}(\omega, K) = -\beta - K^2 \frac{\alpha}{1 + g\alpha} + \frac{\omega}{2M} \nabla^2 \alpha
\]

\[
K^2 = k_0^2 + V_c^2 - 2\omega V_c^2 - 2\omega U_{opt}(\omega, K) = \frac{k_0^2 + V_c^2 - 2\omega V_c^2 + \beta - \frac{\omega}{2M} \nabla^2 \alpha}{1 - \bar{\alpha}}
\]

\[
\bar{\alpha} = \frac{\alpha}{1 + g\alpha}
\]
The real part of the pion optical potential for $\pi$ on $^{16}O$ (left) and $\pi^+$ on $^{208}Pb$ (right) as a function of radius for various pion energies (MeV)
Pion absorption cross sections: examples

Computed and exp. pion absorption cross section on Aluminum as a function of energy

Computed and exp. pion absorption cross section on Gold or Bismuth as a function of energy
**Pion-nucleus interactions: examples**

Computed and exp. pion charge exchange angular distribution for $^{58}\text{Ni}(\pi^+, \pi^0)$ at 160 MeV

(Exp. data: W.J. Burger et al., PRC41, (1990) 2215 and R.D. McKeown et al., PRC24, (1981) 211)

Computed and exp. pion inelastic angular distribution for $^{58}\text{Ni}(\pi^+, \pi^+)$ at 160 MeV
$K^-$ $\bar{K}^0$ -nucleon interactions at medium-low energies

Plenty of $S=1$ baryonic resonances at low energies
$\Lambda\pi$ and $\Sigma\pi$ channels already open at rest
→ Strong $K^-$N interaction

Multichannel analisys needed  Many partial waves contribute
Kaon nuclear potential non-negligible  Hyperons can be bound in nuclei

In PEANUT: in progress
Multichannel partial wave expansion

s wave at low momenta $^2$;  $0 < l < 5$ up to 1.8 GeV/c $^3$

Isospin relations to link different charge states
Mass differences taken into account ( charge exchange)

Kaon-nucleon interactions examples

**Preequilibrium**

For $E > \pi$ production threshold $\rightarrow$ only (G)INC models

At lower energies $\rightarrow$ a variety of preequilibrium models

**Two leading approaches**

- the quantum-mechanical multistep model
- the exciton model

Very good theoretical background

statistical assumptions

complex, difficulties for multiple emission

simple and fast

Exciton model: chain of steps, each ($n_{th}$) step corresponding to $N_n$

“excitons” $\rightarrow$ either a particle above or a hole below the Fermi surface

Statistical assumption: any partition of the excitation energy $E$ among $N$

$N = N_h + N_p$, excitons has the same probability to occur

Step: nucleon-nucleon collision with $N_{n+1} = N_n + 2$ (“never come back” approximation)

Chain end $= equilibrium = N_n$ sufficiently high or excitation energy below threshold

$N_1$ depends on the reaction type and on the cascade history
Preequilibrium emission probability:

\[ P_{x,n}(\epsilon)d\epsilon = \sum n_{px} \frac{\rho_n(U, \epsilon)g d\epsilon}{\rho_n(E)} \frac{r_c(\epsilon)}{r_c(\epsilon) + r_+(\epsilon)} \]

where the density (MeV\(^{-1}\)) of exciton states is given by:

\[ \rho_n(E) = \frac{g(gE)^{n \frac{1}{n}}}{n!(n-1)!} \]

the emission rate in the continuum:

\[ r_c = \sigma_{inv} \frac{\epsilon}{g_x} \frac{(2s + 1)8\pi m}{h^3} \]

and the reinteraction rate:

\[ r_+(\epsilon) = f_{Pauli}(\epsilon, E_F)[\rho_p\sigma_{xp} + \rho_n\sigma_{xn}] \left[ \frac{2(\epsilon + V)}{m} \right]^{1/2} \]

(or from optical potential)

GDH: \( \rho, E_F \) are “local” averages on the trajectory and constrained exciton state densities are used for the lowest lying exciton configurations.
Preequilibrium: modified GDH in PEANUT

- $\sigma_{inv}$ from systematics

- Correlation/formation zone / hardcore effect on reinteractions:

$$\frac{r_c(\epsilon)}{r_c(\epsilon) + r_+(\epsilon)} \rightarrow P_c^{(h\tau)} + P_c^{(co)} + P_c^{(std)}$$

- $P_c^{(h\tau)} = \text{escape prob. in zone} = \max(\tau, \text{hardcore}) \equiv h\tau$
- $P_c^{(co)} = \text{escape/total prob. in zone} = (\text{correlation} - h\tau)$
  (here reinteraction only on non-correlated nucleon specie)
- $P_c^{(std)} = "\text{standard}" \text{ escape/total in remaining zone.}$

- Constrained exciton state densities configurations 1p-1h, 2p-1h, 1p-2h, 2p-2h, 3p-1h and 3p-2h

- Energy dependent form for $g_x$
Preequilibrium: modified GDH in PEANUT II

- Position dependent parameters = point like values:
  - first step: $n_h$ holes generated in the INC step at positions $\vec{x}_i$:
    \[
    \rho^{loc}_{n_h} = \frac{\sum_{i=1}^{n_h} \rho(\vec{x}_i)}{n_h} \quad E^{loc}_{F n_h} = \frac{\sum_{i=1}^{n_h} E_F(\vec{x}_i)}{n_h}
    \]
  - When looking at reinteraction: consider neighborhood:
    \[
    \rho^{nei}_{n_h} = \frac{n_h \rho^{loc}_{n_h} + \rho^{ave}}{n_h + 1} \quad E^{nei}_{F n_h} = \frac{n_h E^{loc}_{F n_h} + E^{ave}}{n_h + 1}
    \]
  - Subsequent steps: go towards average quantities
    \[
    \rho^{loc}_{n_h+1} = \rho^{nei}_{n_h} \quad E^{loc}_{F n_h+1} = E^{nei}_{F n_h}
    \]
Preequilibrium/(G)INC transition

Example of angle integrated $^{90}$Zr(p,xn) at 80.5 MeV calculations with the full algorithm (right), and without the INC stage (left). The various lines show the total, INC, preeq. and evaporation contributions, the exp. data have been taken from M. Trabandt et al. PRC39 (1989) 452
Nonelastic interactions at intermediate energies: examples

Double differential distributions of charged pions produced by neutrons of $\langle E_n \rangle = 383$ (left) and 542 MeV (right). Exp. data have been taken from Buchle et al. NPA515, (1990) 541
Nonelastic interactions at intermediate energies: examples II

Double differential distributions of pions produced by 730 MeV protons. $\pi^{-}$s from Be (left) and $\pi^{+}$ from Pb (right). Exp. data (symbols) have been taken from D.R.F. Cochran et al., PRD6, (1972)
Nonelastic interactions at intermediate energies: examples III

Double differential distributions of $\pi^+$'s produced by 1.6 GeV protons on Pb (left, exp. data from M.C.Lemaire et al., CEA-N-2670) and $\pi^-$ produced by 4 GeV/c protons on Al (right, exp data from H. En’yo et al, PL 159B, 1 (1985)).
Nucleon emission: thin target examples I

Computed (light symbols) and experimental (symbols with lines) double differential distributions for $^{90}\text{Zr}(p,xn)$ (left) and $^{90}\text{Zr}(p,xp)$ at 80.5 MeV. The exp. data have been taken from M.Trabandt et al. PRC39 (1989) 452 and A.A. Cowley et al., PRC43, (1991) 678
Nucleon emission: thin target examples I
Nucleon emission: thin target examples I
Nucleon emission: thin target examples II

Evaporation, fission and nuclear break-up

The evaporation probability for a particle of type \( j \), mass \( m_j \), spin \( S_j \cdot \hbar \) and kinetic energy \( E \) and the total fission probability are given by

\[
P_j = \frac{(2S_j + 1)m_j}{\pi^2 \hbar^3} \int_{V_j} Q_j \Delta_f \sigma_{\text{inv}} \frac{\rho_f(U_f)}{\rho_i(U_i)} E dE
\]

\[
P_F = \frac{1}{2\pi \hbar} \frac{1}{\rho_i(U_i)} \int_{0}^{(U_i-B_F)} \rho_F(U_i - B_F - E) dE
\]

- \( \rho \)'s: nuclear level densities,
- \( Q_j \): reaction \( Q \) for emitting a particle of type \( j \),
- \( U \): excitation energy,
- \( \sigma_{\text{inv}} \): cross section for the inverse process
- \( V_j \): (possible) Coulomb barrier for emitting a particle of type \( j \)

For low mass residuals: Fermi break-up: statistical phase-space production of multiple (excited) fragments

Excitation energy AFTER evaporation \( \rightarrow \gamma \) emission
Evaporation

Latest Improvements to evaporation

- Improved state density \( \rho = \exp(2\sqrt{aU})/U^{\frac{5}{4}} \)
- No Maxwellian approximation for energy sampling
- \( \gamma \) competition in progress

Sub-barrier emission:

\[
\sigma_{\text{inv}}^x = (R + \bar{\lambda})^2 \frac{\hbar \omega_x}{2E} \ln \left[ 1 + e^{\frac{2\pi(E-V_C)}{\hbar \omega_x}} \right]
\]
Residual nuclei predictions: “new” vs “old” evap.

A practical case:
Si damage
α production by neutrons compared to ENDF data
Residual nuclei

The production of residuals is the result of the last step of the nuclear reaction, thus it is influenced by ALL the previous stages

Residual mass distributions are very well reproduced

Residuals near to the compound mass are usually well reproduced

However, the production of specific isotopes may be influenced by additional problems which have little or no impact on the emitted particle spectra

- Extreme sensitivity to details of evaporation
- Nuclear structure effects
- Lack of spin-parity dependent calculations in most MonteCarlo models
- Difficulty to model fragmentation processes, that populate A<20-30 for medium/heavy target nuclei.
- Isomer production: an open question
- Interesting cross section values typically spans four order of magnitudes
Residual nuclei predictions: a look at the isotope table
Residual nuclei: the mass distribution at high energies

Experimental and computed residual nuclei mass distribution following for Ag(p,x)X at 300 GeV (top) and Au(p,x)X at 800 GeV (bottom).
Residual nuclei predictions: examples

Comparison between computed and measured (A.S. Iljinov et al., Landolt-Börnstein, Vol. 13a (1991)) isotope production by protons on natural Cobalt
Residual nuclei predictions: “new” vs “old” evap.

Comparison between isotope yields computed with the new (left) and (right) evaporation model in FLUKA.
Neutron transport below 20 MeV

- ENEA multigroup cross-sections: 72 groups, \( \approx 100 \) elements/isotopes
- Gamma-ray generation, different temperatures, Doppler broadening, self-shielding
- Transport: standard multigroup transport with photon and fission neutron generation
- Detailed kinematics and recoil transport for elastic and inelastic scattering on hydrogen and for \( ^{14}N(n, p) \), \( ^{10}B(n, \alpha) \) and \( ^{6}Li(n, x) \)
- Correlated capture gamma generation for selected isotopes
- Photons transported with EMF
- Kerma factors to calculate energy deposition
- Residual nuclei production
An example of calculated cooldown curve

Cooling curves for residual activity for a Stainless Steel, Stainless Steel+CH$_2$ or Iron target (40 cm radius, 100 cm long) irradiated by $10^{11}$ 5 GeV protons s$^{-1}$ for one month
Evolution of residual nuclei: SS/Iron target

Computed residual activities (Bq) as a function of the isotope atomic number Z and neutron excess N-Z for an AISI304 target (40 cm radius and 100 cm long) irradiated by $10^{11}$ 5 GeV protons s$^{-1}$ for one month: after 60 s (top left), 1 day (top right) and after 1 year (right)
Neutron production examples: thick targets

Simulated (dashed histogram) and experimental (symbols) neutron double differential distributions out of stopping length targets for 113 MeV protons on U (left, data from M. M. Meier et al., Nucl. Sci. Eng. 110, (1992) 299) and 500 MeV protons on Pb and 256 MeV protons on uranium (right, S. Meigo et al., JAERI-Conf 95-008, (1995), 213)
**EMF : ElectroMagnetic Fluka**

- **Photoelectric**: fluorescence, angular distribution, Auger, polarization
- **Compton and Rayleigh**: atomic bonds, polarization
- **Pair production**: correlated angular and energy distribution; also for $\mu$
- **Photonuclear**: see later; also for $\mu$
- **Bremsstrahlung**: LPM, angular distribution, finite at tip, ... also for $\mu$
- **Bhabha and Møller scattering**
- **Positron annihilation**: at rest and in flight
- **$\mu^-$ capture**: at rest
- **Optical photon**: (Čerenkov) production and transport
LEP dismantling: a calculational nightmare

Request: demonstrate that ALL activities are below 1/10 of the 1996 European Directive limits (around 10 Bq/g) after 10 year operation

An almost unaffordable task for a MC:
Starting from an electron beam,
simulate the extremely rare photon induced nuclear interactions
with such an accuracy as to determine the residual nuclei.

EXPERIMENT: samples of different materials on LEP beam dumps.
- Irradiation time: 5 months, at about 20 cm from the beam axis
- Specific activity of the radionuclides detected in the samples were compared with FLUKA calculations
- The measured activities are so low (few Bq/g) that even the experimental measurement is difficult
Photonuclear Interactions

- **Giant Resonance** interaction
- **Quasi-Deuteron** effect
- interaction in the **Delta Resonance** energy region
- **Vector Meson Dominance** in the high energy region
- INC, preequilibrium and evaporation via the **PEANUT** model
- Possibility to bias the photon nuclear inelastic interaction length to enhance interaction probability

In not many other existing transport codes photonuclear reactions are simulated over the whole energy range
Yield of neutrons per incident electron as a function of initial electron energy. Open symbols: FLUKA, closed symbols: exp. data. **Left:** Pb, 1.01 (lower points) and 5.93 (upper) $X_0$ **Right:** U, 1.14 and 3.46 $X_0$
Pb(γ,xn) (exp. data NPA367, 237 (1981), NPA390, 221 (1982))
**LEP activation: some experimental results**

<table>
<thead>
<tr>
<th>Radio nuclide</th>
<th>$T_{1/2}$ (d)</th>
<th>Specific Activity (Bq/g)</th>
<th>Ratio (F/E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{46}$Sc</td>
<td>83.8</td>
<td>0.13</td>
<td>0.065</td>
</tr>
<tr>
<td>$^{48}$V</td>
<td>15.97</td>
<td>0.31</td>
<td>0.52</td>
</tr>
<tr>
<td>$^{51}$Cr</td>
<td>27.7</td>
<td>4.12</td>
<td>2.7</td>
</tr>
<tr>
<td>$^{52}$Mn</td>
<td>5.6</td>
<td>0.17</td>
<td>0.74</td>
</tr>
<tr>
<td>$^{54}$Mn</td>
<td>312.2</td>
<td>3.54</td>
<td>2.9</td>
</tr>
<tr>
<td>$^{59}$Fe</td>
<td>44.5</td>
<td>0.028</td>
<td>0.0088</td>
</tr>
<tr>
<td>$^{56}$Co</td>
<td>77.7</td>
<td>0.29</td>
<td>0.46</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td>271.8</td>
<td>1.3</td>
<td>1.1</td>
</tr>
<tr>
<td>$^{58}$Co</td>
<td>70.9</td>
<td>2.65</td>
<td>1.4</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>5.27</td>
<td>0.18</td>
<td>0.085</td>
</tr>
<tr>
<td>$^{95}$Nb</td>
<td>34.9</td>
<td>0.038</td>
<td>0.013</td>
</tr>
</tbody>
</table>

*Stainless Steel sample on the LEP electron dump. The exp. points have a systematic error of $\approx 20\%$ (A. Fassò et al. CERN-TIS-99-011-RP-CF/SLAC-PUB-8214 and CERN-TIS-99-012-RP-CF/SLAC-PUB-8215)*
Charged particle transport

Ionization energy losses (below $\delta$ threshold)

Latest recommended values of ionization potential and density effect parameters implemented (Sternheimer, Berger & Seltzer) (can be overridden on user’s request)
Special treatment of positron $dE/dx$ (Kim et al. 1986)
a new general approach to ionization fluctuations (see later)

Multiple coulomb scattering

path length correction, lateral displacement, angle correlation
Soft approach to boundaries
Single scattering available, automatic if needed
Screening and spin-relativistic correction
Fully coupled to magnetic field transport
Ionization Fluctuations

The FLUKA approach:

- based on general statistical properties of the cumulants of a distribution (in this case a Poisson distribution convoluted with $d\sigma/dE$)
- integrals can be calculated **analytically** and **exactly a priori** $\implies$ minimal CPU time
- **applicable to any kind of charged particle**, taking into account the proper (spin-dependent) cross section for $\delta$ ray production
- the **first 6 moments** of the energy loss distribution are reproduced
  \[ k_n = \langle (x - \langle x \rangle)^n \rangle \]
Ionization Energy losses

Experimental and calculated energy loss distributions for 2 GeV/c positrons (left) and protons (right) traversing 100 μm of Si

4J.Bak et al., NPB288, 681 (1987)
FLUKA mcs algorithm

“New algorithm” additions: (work in progress)

- Position angle, $\eta$, randomly sampled around the “correct” Molière
distribution trying to correlate correctly with the scattering angle
- Azimuthal angle between the position and velocity vectors randomly
  sampled
- “Polygonal” step path in order to maximize energy deposition
  accuracy and to help in getting correct boundary effects
Graphical example

Tracklength vs depth distribution for 0.5 MeV $\epsilon^-$ on Au, 5% step, for N=1,...,16 substeps and single scattering for the “old” (left) and “new” (right, with polygonal approach) algorithms
Heavy ions

Heavy ion transport and interactions are presently under development in FLUKA:

- Ionization energy losses already implemented
  - Up-to-date effective charge parametrizations
  - Energy loss straggling according to:
    * “normal” first Born approximation
    * Charge exchange effects (dominant at low energies, ad-hoc model developed for FLUKA)
    * Mott cross section and nuclear form factors (high energies) (in progress)
- Multiple scattering already implemented
- High energy A-A interactions \((E > 5 - 10 \text{ GeV/u})\): interface to DPMJET test phase
- Low energy A-A interactions: extension of the PEANUT model almost ready for tests with \(\alpha's\)
dE/dx and straggling of heavy ions

Experimental (red) (R.Bimbot, NIMB69 (1992) 1) and FLUKA (blue) stopping powers of Argon and Uranium ions in different materials and at different energies.
dE/dx and straggling of heavy ions

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Target</th>
<th>thickness (mg/cm²)</th>
<th>FWHM (keV)</th>
<th>Exp</th>
<th>FLUKA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C</td>
<td>Al</td>
<td>0.217</td>
<td>74.5 ±3</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>Al</td>
<td>0.110</td>
<td>92 ±2</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>Al</td>
<td>0.246</td>
<td>147 ±3</td>
<td>144</td>
<td></td>
</tr>
<tr>
<td>$^{16}$O</td>
<td>Al</td>
<td>0.457</td>
<td>202 ±2</td>
<td>198</td>
<td></td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>Al</td>
<td>0.315</td>
<td>290 ±30</td>
<td>356</td>
<td></td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>Al</td>
<td>0.990</td>
<td>521 ±20</td>
<td>638</td>
<td></td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>Au</td>
<td>0.053</td>
<td>98 ±20</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>$^{32}$S</td>
<td>Au</td>
<td>3.492</td>
<td>820 ±20</td>
<td>1092</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Al</td>
<td>0.321</td>
<td>780 ±40</td>
<td>735</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Al</td>
<td>0.530</td>
<td>1000 ±35</td>
<td>949</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Al</td>
<td>0.990</td>
<td>1375 ±50</td>
<td>1297</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Au</td>
<td>0.053</td>
<td>250 ±10</td>
<td>275</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Au</td>
<td>1.186</td>
<td>1200 ±50</td>
<td>1255</td>
<td></td>
</tr>
<tr>
<td>$^{127}$I</td>
<td>Au</td>
<td>3.800</td>
<td>2250 ±90</td>
<td>1932</td>
<td></td>
</tr>
</tbody>
</table>

Measured (S. Ouichaoui et al. NIM B164-165 (2000) 259) and computed (FLUKA) straggling for 2 MeV/amu $^{12}$C, $^{16}$O, $^{32}$S ions and 1.467 MeV/amu $^{127}$I ions
Heavy ions at relativistic energies: DPMJET

DPMJET

Authors: R. Engel†, J. Ranft*, and S. Roesler&
† Bartol, * Siegen University, & CERN

Nucleus-Nucleus interaction code \(^5\) for collisions from \(\approx 5-10 \) GeV/n till the highest cosmic ray energies \((10^{18} - 10^{20} \) eV\)

Applications of DPMJET

- Predictions for heavy ion experiments at present and future accelerators (i.e. ALICE at LHC)
- Simulations of Cosmic Ray cascades in the HEMAS-DPM code used by the MACRO Collaboration
- Simulations of Cosmic Ray cascades in the CORSIKA code (Karlsruhe)

DPMJET: examples of performances

Rapidity distribution of negative particles for 158 AGeV/c S-S and S-Ag collisions (left) and of positive pions and kaons for 158 AGeV/c Pb-Pb collisions (right). Experimental data from the NA-35 and NA-44 collaborations are compared with DPMJET predictions.
Cascading/evaporation in A-A collisions (from ZPC71, 75 (1996))

\[ \text{Au-Emulsion, } E_{\text{Lab}} = 11.6 \text{ GeV/nucleon} \]

Black particle multiplicity distributions in gold-emulsion interactions compared with exp. data (ZPC65, 421 (1995))
Cascading/evaporation in A-A collisions (from ZPC71, 75 (1996))

Correlations between shower ($N_s$) and heavy ($N_h$) particle multiplicities in sulfur-emulsion interactions, compared with exp. data (ZPC65, 421 (1995))

Correlations between gray ($N_g$) and black ($N_b$) particle multiplicities in sulfur-emulsion interactions, compared with exp. data (ZPC65, 421 (1995))
Presently: DPMJET-II.53, upgrade to DPMJET-3 in progress

Initialization

Cross sections pre-computed by DPMJET, tabulation is used by FLUKA
Glauber impact parameter distributions have been pre-computed for a
complete matrix of projectile-target combinations up to \( A=246 \) over the
entire available energy range (3 A GeV–1.5 \( \cdot \) 10\(^6\) A GeV in N-N cms).

Interface call at begin and end of single interactions
Reaction products given back to be transported by FLUKA
Residual nuclei deexcitation is performed in FLUKA
Integral Glauber impact parameter distributions for the extreme energy bins and one projectile-target combination.

$E_{lab} = 6.3 \cdot 10^6$ ATeV.

Symbols: computed values

Lines: interpolation used by FLUKA
**Muon Capture**

An exotic source of neutron background *(See background at nTOF)*

Basic weak process: \( \mu^- + p \rightarrow \nu_\mu + n \)

\( \mu^- \) at rest + atom \( \rightarrow \) excited muonic atom \( \rightarrow \) x-rays + g.s muonic atom

Competition between \( \mu \) decay and \( \mu \) capture by the nucleus.

In **FLUKA**: Goulaud-Primakoff formula

\[ \Lambda_c \propto Z_{eff}^4 \], calculated \( Z_{eff} \), Pauli blocking from fit to data.

\[ \frac{\Lambda_c}{\Lambda_d} = 9.2 \cdot 10^{-4} \] for H, \hspace{1cm} 3.1 for Ar, \hspace{1cm} 25.7 for Pb

Nuclear environment (Fermi motion, reinteractions, deexcitation..) from the **FLUKA** intermediate-energy module PEANUT

Slow projectile, low energy transfer (neutron E=5 MeV on free p)

Experimentally: high energy tails in n-spectra

Beyond the simple one-body absorption

Good results from addition of two-nucleon absorption
Muon Capture-II

Neutron spectra following muon capture on Lead
Dots: experimental data
histograms: FLUKA calculations
The three curves correspond to a percentage of 2-body absorption of 0, 20%, and 100%.
Emitted:
1.7 neutrons/capture
0.002 protons/capture
Muon Capture-III

Neutron spectra following muon capture on Calcium
histograms: FLUKA calculations
Emitted:
0.62 neutrons/capture
0.27 protons/capture
the nTOF facility

- High flux -high resolution spallation neutron source
  - Wide energy range: thermal up to GeV
  - High flux: \( \approx 6 \times 10^5 n/cm^2/7 \cdot 10^{12} pr @ 200 m \)
  - Resolution: \( \Delta E/E^2 \times 10^{-4} @ 1 \text{ keV}, 2 \times 10^{-3} @ 1 \text{ MeV} \)
  - Low (expected) background: \( 10^{-6} \)

- Proton Beam
  - CERN-PS: 20 GeV/c, \( l_p = 4 \) bunches \( \times 7 \times 10^{12} pr/14.4 \text{ s} \)

- Measurements of neutron induced cross sections
  - ADS applications
  - Astrophysics

June 2001: first measurements facing a background > 50 times more than expected! \( \rightarrow \) trying to understand (A.Ferrari, C.Rubbia, V.Vlachoudis, SL-EET 2001-036)
nTOF background: Simulation setup

Top view of TT2A Tunnel Geometry used in the simulations (a); zoom in target area (b); and experimental area (c).
Simulated muon fluence at the entrance of the exp. station per $7 \times 10^{12}$ protons
Energy spectrum (dn/dln(E)) of the muons entering the experimental area
Computed neutron fluence (n/cm²) inside the experimental area (from the top) for a standard pulse of $7 \times 10^{12}$ protons.
nTOF Simulated neutron energy spectrum

Background Neutron Energy Spectrum at Exp. Area

Background neutron entries split into different sources
nTOF Simulated neutron time distribution

Background neutron time distribution divided into the different components
Computed muon fluence ($\mu$/cm$^2$) along the n_TOF tunnel for a standard pulse of $7 \times 10^{12}$ protons with and without the extra iron shield, and with the shield with a 1 m thick concrete basement. This is an average over the $\pm 1$ m around the tube position.
nTOF Provisional (October 2001) muon wall layout: picture
nTOF C6D6 Gold measurements: october vs may cont.

C6D6 spectra with a $^{197}$Au sample: may 2001 (left), and october 2001 (right)
nTOF $^3$He: measured vs simulated time spectra

$^3$He Response Small Poly=81cm

Count Rate (dn/dlnE/10^{-12}pr)

Neutron Time (µs)

Simulation of $^3$He @4

#0 Measurement @4

Measured (red) versus computed (black) $^3$He + poly. 81 mm time spectra. The comparison is absolute
Different Applications

The FLUKA development, its accuracy and versatility originated to a great deal from the needs of the author experiments, and new applications arise from new code capabilities, with a continuous interplay which is always physics driven. Examples are given below.

- **Neutrino physics and Cosmic Ray studies: initiated within ICARUS**
  - Neutrino physics: ICARUS, CNGS, NOMAD, CHORUS
  - Cosmic Rays: First 3D $\nu$ flux simulation, Bartol, MACRO, Notre-Dame, AMS

- **Accelerators and shielding: the very first FLUKA application field**
  - Beam-machine interactions: CERN, NLC, LCLS
  - Radiation Protection: CERN, INFN, SLAC, Rossendorf
  - Waste Management and environment: LEP dismantling, SLAC

- **Background and radiation damage in experiments: Pioneering work for ATLAS**
  - all LHC experiments, NLC
Different Applications

• Dosimetry, radiobiology and therapy:
  – Dose to Commercial Flights: E.U., NASA
  – Dosimetry: INFN, ENEA, GSF, NASA
  – Radiotherapy: Already applied to real situations (Optis at PSI, Clatterbridge)
  – Dose and radiation damage to Space flights: NASA, ASI

• Calorimetry:
  – ATLAS test beams
  – ICARUS

• ADS, spallation sources (FLUKA+EA-MC, C.Rubbia et al.):
  – Energy Amplifier
  – Waste trasmutation with hybrid systems
  – Pivotal experiments on ADS (TARC, FEAT)
  – nTOF
The LAr TPC technique is based on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized (i.e. a set of fine pitch wire grids) it is possible to realize a massive "electronic bubble chamber", with superb 3-D imaging.
Calorimetry in imaging, fully sensitive liquid Argon

Liquid argon is a non-compensating medium. When used in a time projection chamber like ICARUS the effect is exacerbated by the relatively low electric field (≈ 300–500 V/cm)

However, the medium appears as a completely homogeneous volume with very high readout granularity

\[\downarrow\]

From the event visualisation and from the local charge deposition density, it is possible both to distinguish between electromagnetic and hadronic components of a shower and to approximately correct for the recombination effects.
Calorimetry in imaging, fully sensitive liquid Argon

Quenching correction

Let assume that each elementary cell contains only one crossing track, the recombination effect can be unfolded using the collected charge and cell width to construct the observed dQ/dx and solving the recombination expression for the “actual” dE/dx. Despite its simplicity, the procedure is very effective in recovering most of the recombination, particularly when the Argon is doped with TMG

Compensation correction

Let us assume that electromagnetic energy deposition can be distinguished from hadronic one, the total energy of a shower is obtained as the sum of two terms

\[ E = w \times (Q_{em} + \alpha \times Q_{had}), \]

where \(\alpha\) is the compensation factor. For pure argon, \(\alpha\) is about 1.5 (2.8) with and without quenching corrections respectively. The same figures for TMG-doped argon are 1.5 and 2.0
### ICARUS: resolutions for pions

**Expected hadronic resolution for pions**

<table>
<thead>
<tr>
<th>Medium</th>
<th>Compensation</th>
<th>Quench corr.</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure argon</td>
<td>no</td>
<td>no</td>
<td>27%/$\sqrt{E}$ $\pm$ 8%</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>no</td>
<td>24%/$\sqrt{E}$ $\pm$ 4%</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>yes</td>
<td>18%/$\sqrt{E}$ $\pm$ 6%</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>yes</td>
<td>16%/$\sqrt{E}$ $\pm$ 1%</td>
</tr>
<tr>
<td>TMG doped argon</td>
<td>no</td>
<td>no</td>
<td>20%/$\sqrt{E}$ $\pm$ 6%</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>no</td>
<td>16%/$\sqrt{E}$ $\pm$ 2%</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>yes</td>
<td>15%/$\sqrt{E}$ $\pm$ 5%</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>yes</td>
<td>12%/$\sqrt{E}$ $\pm$ 0.2%</td>
</tr>
<tr>
<td>No quenching</td>
<td>no</td>
<td>-</td>
<td>15%/$\sqrt{E}$ $\pm$ 5%</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>-</td>
<td>12%/$\sqrt{E}$ $\pm$ 0.1%</td>
</tr>
</tbody>
</table>

Expected resolution in the liquid target for pions with and without TMG doping, showing the effect of the offline compensation and quench correction. For reference, the resolution that would be obtained with no recombination effects is also listed.
Neutrino interactions in PEANUT: the NUX-FLUKA event generator

Authors: A. Ferrari (CERN/INFN), A. Rubbia (ETH Zurich), P.R. Sala (ETH/INFN)

Features:

- Full use of all sophisticated nuclear physics of PEANUT
- Quasielastic event generator built-in
- RES and DIS: nucleon density, position and Fermi motion via PEANUT → νN interaction via NUX (A.Rubbia, originally developed for NOMAD), → all secondaries propagated with PEANUT. Fully integrated one in the other in a single code → “correct” account for kinematical effects on cross section due to Fermi motion and for Pauli blocking

The comparison with NOMAD data are due to A. Bueno, A. Rubbia, ETH Zurich
Neutrino quasi-elastic events

ICARUS prototype: two views in Liquid Argon, 10 GeV $\nu_\mu$ CC

“Clean” event:

$\nu_\mu \ n \rightarrow \mu^- \ p$

$\mu \ p \ \gamma$

vertex 1
SOURCE
9459 MeV
Neutrino quasi-elastic events

ICARUS prototype: two views in Liquid Argon, 10 GeV $\nu_\mu$ CC

Complex event:
$\nu_\mu \ n \rightarrow \mu^- \ p$

$1 \mu, \ 8 \ p, \ 2 \ \pi, \ 1 \ \pi^0, \ 4 \ n, \ 1 \ \alpha, \ 3 \ \gamma$
The *NUX-FLUKA* event generator: comparison with NOMAD

![Graphs showing comparison between Nux MC and NOMAD data for various parameters like $P_T$ and multiplicity.](image-url)

Experiment
Protons from the CERN PS, 2.5 or 3.57 GeV/c
Lead target, 334 ton, 99.99% purity
64 Instrumentation holes, different detectors to measure neutrons from thermal to MeV
Simulations: EA MC
Spallation and transport down to 19.6 MeV: FLUKA
Neutron transport and interactions, and target evolution: new code (C.Rubbia et al)
Neutron production examples: TARC (PLB458 (1999) 167)
The CERN reference radiation facility – CERF

• A reference radiation facility (called CERF) for the calibration and intercomparison of dosimetric devices in high energy stray radiation fields is available at CERN since 1993, on the H6 beam line in the North Area.

• Hadron beams with momentum of either 120 or 205 GeV/c are stopped in a copper target, which can be installed in two different positions. On top and on side of these two positions, the secondary particles produced in the target are filtered by a shielding made up of either concrete or iron.

• The facility is partially supported by the European Commission in the framework of a research program for the assessment of radiation exposure at civil flight altitudes.

• The composition of the CERF field is accurately known by means both of FLUKA calculations and measurements with several instruments which nicely agree each other. Some examples of comparisons of computed vs measured data are presented in the following.
Calibration of the LINUS rem counter (left) and of three Bonner spheres (right) with monoenergetic neutron beams at PTB–Braunschweig and with semi-monoenergetic neutron beams at PSI (full symbols), compared with simulations (dashed histos and open circles)
Top (left, one side removed) and side (right, roof removed) views of the CERF facility with the measuring positions.
## CERF: some results

<table>
<thead>
<tr>
<th></th>
<th>Experimental cts/PIC</th>
<th>FLUKA cts/PIC</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td><strong>Concrete Top “E”</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LINUS rem counter*</td>
<td>0.364</td>
<td>0.409</td>
<td>2.2</td>
</tr>
<tr>
<td>SNOOPY rem counter*</td>
<td>0.200</td>
<td>0.207</td>
<td>3.3</td>
</tr>
<tr>
<td>233 sphere</td>
<td>0.788</td>
<td>0.899</td>
<td>3.7</td>
</tr>
<tr>
<td>178 sphere</td>
<td>0.989</td>
<td>1.01</td>
<td>3.4</td>
</tr>
<tr>
<td>133 sphere</td>
<td>1.02</td>
<td>0.981</td>
<td>3.2</td>
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<tr>
<td>108 sphere</td>
<td>0.942</td>
<td>0.883</td>
<td>3.1</td>
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<td>83 sphere</td>
<td>0.704</td>
<td>0.717</td>
<td>3.1</td>
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<td><strong>Iron Top “C”</strong></td>
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<tr>
<td>Experimental</td>
<td>1.78</td>
<td>1.68</td>
<td>2.1</td>
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<tr>
<td>FLUKA</td>
<td>1.83</td>
<td>1.71</td>
<td>2.0</td>
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<tr>
<td>233 sphere</td>
<td>9.28</td>
<td>9.23</td>
<td>2.0</td>
</tr>
<tr>
<td>178 sphere</td>
<td>16.1</td>
<td>16.9</td>
<td>1.9</td>
</tr>
<tr>
<td>133 sphere</td>
<td>19.2</td>
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<td>1.9</td>
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<tr>
<td>108 sphere</td>
<td>17.7</td>
<td>19.2</td>
<td>1.9</td>
</tr>
<tr>
<td>83 sphere</td>
<td>11.2</td>
<td>12.1</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Comparison between the FLUKA predictions and the experimental response of the various detectors in stray radiation fields at CERN \(^6\). The percent statistical uncertainty (%) is indicated.

\(^6\)C. Birattari et al., Rad. Prot. Dos, 76 (1998) 135
The OPTIS beam at PSI

Context: PSI therapy unit: 72 MeV proton beam, fully-modulated
Goal: Full understanding of its physical and radiobiological features
Emphasis: relationship between dosimetical quantities and biological effects
Assumption: clustered DNA damage is an estimator for cell inactivation

Solution: Combined physical-biophysical simulation of the OPTIS beam
The input data used in the simulation were fixed a priori on the basis of informations provided by PSI.

No free parameter was introduced and no a posteriori fit to experimental data was performed.

The results were directly compared with the measurements of the physical dose and with experimental data on cell survival 7.

7 M. Biaggi et al., NIMB 159 (1999) 89
The OPTIS beam at PSI II

Simulation approach:

- Full simulation of all beam line elements including the rotating beam shapers used for generating the Spread Out Bragg Peak (SOBP) and the actual beam emittance (technical part)

- Simulation of primary and secondary radiation fields associated with the proton beam and their interactions with the phantom tissue (physical part)

- “Weighting” of each track segment with the particle/energy dependent probability of inducing complex DNA lesions (CL) as obtained from track structure simulations of DNA damage using the MOCA code for the time being and the PARTRAC code in the future (biophysical part)

---

8 Operatively defined as two or more single-strand breaks on each DNA strand within 30 base pairs
Absorbed Dose and its components

Measured (red) and calculated (green) depth-dose curves in perspex of 72 MeV modulated proton beam. The calculated dose is split into the contribution of primary protons (blue), electrons and photons (purple) and secondary hadrons including ions (cyan).
Calculated relative number of complex lesions per cell. For each component the upper (full) line represents the yield of complex lesions/cell, whereas the lower curve (dashed) represents the yield that one would obtain assuming an effectiveness equal to that of x-rays.
OPTIS: relative effectiveness of protons wrt x-rays

Simulation (blue curve): ratio between DNA complex lesions/cell (CL/cell) after irradiation with 2 Gy in the 72 MeV proton beam and with x-rays. Experimental data (red points): ratio between lethal lesions/cell (LL/cell) in V79 cells after irradiation with 2 Gy in the 72 MeV proton beam and with x-rays.
A Human Phantom for dosimetric calculations

For each organ:

- Spatial distribution of fluences of particles of different types and energies
- Estimation of radiation effects

Already in use for:

- Calculations of fluence-to-ambient dose equivalent and fluence to effective dose conversion factors for $\gamma$, $e^+/e^-$, $p$, $n$, $\pi$ and $\mu$ up to very high energies (10 TeV).

Possible future applications:

- Estimation of protection properties of different shield designs in particular field conditions (aircrafts, spacecrafts)
Cosmic Ray Showers


Benchmarks and Applications: Muon and hadron fluxes, Aircraft exposure

Ingredients

- Primary ray spectrum and composition, solar modulation
- Atmosphere description (3 Dimensional)
- Particle transport and decay (3-D)
- Hadronic interactions
-Geomagnetic effects

Up to now, primary nuclei are splitted into nucleons before interacting
3D effects in $\nu$ angular distributions

Sub-GeV flux at Kamioka

\[ \frac{\nu}{cm^2/sec/sr/GeV} \]

\[ \nu_\mu \]

\[ \nu_e \]

\[ \bar{\nu}_\mu \]

\[ \bar{\nu}_e \]
Comparison FLUKA 3D - CAPRICE 94 Negative

Hadron/muon fluxes in the atmosphere: /n Astropart. Phys. 17 477

(2002)
Comparison FLUKA 3D - CAPRICE 94 Positive Muon Flux (GeV/c cm$^2$ sr s)

Positive Muon Flux (GeV/c cm$^2$ sr s)

X (g/cm$^2$)

(2002)

Hadron/muon fluxes in the atmosphere: +\+ Astropart. Phys. 17 477
AMS (astro-ph/0111111)

Protons and leptons below the geomagnetic cutoff have been measured by the AMS experiment at altitudes 370-390 Km, latitude ±51.7°.

Downgoing proton flux, simulation(solid line) AMS data (triangles). $\Theta_M$ is the geomagnetic latitude in radians.
AMS

Upgoing Protons

Downgoing $e^{\pm}$
Radiation Field at Aircraft altitudes

S. Roesler, W. Heinrich, H. Schraube, SLAC-PUB-8968
Courtesy of S. Roesler

Ionizing radiation as a function of elapsed time after take-off, on commercial flights from San Francisco and Rio de Janeiro to Frankfurt
Ionizing radiation as function of vertical rigidity cutoff on commercial flights.
Neutron Spectra at Ground level

S. Roesler, W. Heinrich, H. Schraube, SLAC-PUB-8968 Courtesy of S. Roesler

Ground-level neutron spectra at the Schneefernerhaus (2660 m a.s.l). Calculations with different humidity and soil
Doses to commercial flight crews *(Rad. Prot. Dosim. 93 101 and 96 219 (2001))*

Calculated effective dose as a function of altitude for a vertical rigidity cutoff of 0.4 GV at solar minimum (open circles), and at solar maximum (open squares), and for a cutoff of 17.6 GV (black circles) Contributions of various radiation components to the effective dose rate as a function of the vertical cut-off rigidity at solar minimum, and for an altitude of 10580 m
A. Ferrari, M. Pelliccion and T. Rancati, Rad. Prot. Dos. 2001
A comparison of calculated ambient dose equivalent rates with in–flight measurements for different altitudes and geomagnetic latitudes (μSv/h).

<table>
<thead>
<tr>
<th>$B_m$ (°)</th>
<th>Vertical cut–off (GV)</th>
<th>FL 310 (9450 m)</th>
<th>FL 330 (10060 m)</th>
<th>FL 350 (10670 m)</th>
<th>FL 370 (11280 m)</th>
<th>FL 390 (11890 m)</th>
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<tr>
<td>−25.98</td>
<td>6.1</td>
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<td>2.8</td>
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<td>3.5</td>
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<td>2.2</td>
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<td>1.5</td>
<td>1.7</td>
<td>1.9</td>
<td>2.0</td>
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<td>11.27</td>
<td>15.0</td>
<td>1.4</td>
<td>1.7</td>
<td>1.7</td>
<td>1.9</td>
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<td>15.0</td>
<td>1.3</td>
<td>1.5</td>
<td>1.7</td>
<td>1.9</td>
<td>2.0</td>
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<td>1.6</td>
<td>2.0</td>
<td>2.0</td>
<td>2.3</td>
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<td>3.2</td>
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<td>33.40</td>
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<td>2.0</td>
<td>2.2</td>
<td>2.5</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>33.49</td>
<td>9.0</td>
<td>2.2</td>
<td>2.6</td>
<td>2.7</td>
<td>2.7</td>
<td>3.9</td>
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<td>45.57</td>
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<td>4.1</td>
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<td>6.7</td>
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<tr>
<td>65.49</td>
<td>0.4</td>
<td>4.5</td>
<td>5.4</td>
<td>6.2</td>
<td>7.3</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Differences < 20 % for 78% of data, <34 % for all
Data (upper lines) : U.J. Schrewe, NIM A422, 621 (1999)
The TIARA neutron propagation experiment

- Source term: neutron spectra generated by 43 and 68 MeV protons on a $^7$Li target, carefully measured with TOF techniques
  Quasi-monoenergetic neutrons of 40 MeV and 65 MeV

- Attenuation of the neutron beam at different depths in concrete and iron shields, both on axis and off-axis (*critical for elastic scattering!!*)

- Emerging neutron spectra measured with liquid scintillator detectors (the high energy component) and Bonner spheres (the low energy component)

The TIARA exp.: FLUKA vs exp. data (concrete on axis)

Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra after different concrete thicknesses (from 25 to 150 cm), on axis. The neutrons are generated by $^7\text{Li}(p,n)$ at 43 (left) and 68 MeV (right)
The TIARA exp.: FLUKA vs exp. data (iron on axis)

Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra after different iron thicknesses (from 20 to 100 cm), on axis. The neutrons are generated by $^7$Li(p,n) at 43 (left) and 68 MeV (right).
The TIARA exp.: FLUKA vs exp. data (concrete off axis)

Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra off axis (from 0 to 40 cm) after 25 (left) and 50 cm thick concrete shields. The neutrons are generated by $^7$Li(p,n) at 43 (left) and 68 MeV (right).
The TIARA exp.: FLUKA vs exp. data (iron off axis)

Comparison of simulated (dashed histogram) and measured (symbols) neutron spectra off axis (from 0 to 40 cm) after 20 (left) and 40 cm thick iron shields. The neutrons are generated by $^7\text{Li}(p,n)$ at 43 (left) and 68 MeV (right)
ATLAS combined calorimeter test beam

LAr electromagnetic calorimeter

Detail of the accordion structure

Sampling term:
e at $\eta = 0.28$
MC at 10 and 100 GeV

Exp. $\frac{\sigma}{E} = \frac{9.8 \pm 0.4\%}{\sqrt{E}}$

FLUKA $\frac{\sigma}{E} = \frac{9.2 \pm 0.3\%}{\sqrt{E}}$
LAr electromagnetic calorimeter

Phi modulation of the response

Longitudinal Development:
$e$ at $\eta = 0.28$
Energy in sampling 1 / total

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>E1/E Data</th>
<th>E1/E Fluka</th>
<th>r.m.s. Data</th>
<th>r.m.s. Fluka</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.68</td>
<td>0.69</td>
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<td></td>
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<tr>
<td>287</td>
<td>0.61</td>
<td>0.58</td>
<td>0.091</td>
<td>0.094</td>
</tr>
</tbody>
</table>
300 GeV $\mu$ in ATLAS combined calo

Calibration in electron scale
electronic noise added

E.M. Calorimeter

 TILE Calorimeter

$E. \ M. \ calo$

$Tile \ calorimeter$

Exp

FLUKA

0 2000 4000 6000 8000 10000

0 1 2 3 4 5 6 7 8 9 10

$ GeV$

$ GeV$

peak

peak

4567

89
300 GeV $\mu$ in ATLAS combined calo

Total and partial energy losses for muons in lead as a function of muon energy

Energy loss difference for 300 GeV muons in lead using different formulations for bremsstrahlung.
300 GeV $\mu$ in ATLAS combined calo

Total experimental spectrum in the comparison between calculated and experimental spectra in the tile calorimeter for $\nu > 0.01$
Comparison with PION data

Cut on mip in presampler  
Cut on beam position (beam chambers)

**FLUKA**: Calibration in electron scale
**FLUKA**: Scintillator quenching included, Noise added
**FLUKA**: Proton contamination taken into account

Energy reconstructed using the “benchmark” technique:

\[
E_0 = E_{em} + a \cdot Q_{had} + b \cdot \sqrt{|E_{em3} \cdot a \cdot Q_{had1}|} + c \cdot E_{em}^2
\]  

(1)

*All parameters fixed to minimize \( \frac{\sigma}{E_0} \) at 300 GeV*
Comparison with PION data

1994 Data: Experimental electron scale calibration available

<table>
<thead>
<tr>
<th></th>
<th>$a$ (GeV/pC)</th>
<th>$b$</th>
<th>$c$ (GeV$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>FLUKA</td>
<td>0.172(2)</td>
<td>0.38(2)</td>
<td>-0.00038(10)</td>
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<tr>
<td>EXP</td>
<td>0.172</td>
<td>0.44</td>
<td>-0.00038</td>
</tr>
</tbody>
</table>
Comparison with PION data

Longitudinal shower development

1994 Data

Energy spectrum in E.M. calo

1994 ATLAS Combined Calo

Energy/Int. length

50 GeV π

0 2 4 6 8 10

Int. lengths

Energy/Int length

300 GeV π

0 2 4 6 8 10

Int. lengths

Alfredo Ferrari

Rogendorf, 29 August 2002
Comparison with pion data

Energy Resolution

1996 Data:

Less electronic noise
Better presampler
No electron calibration

MC: (58.3 %/ $\sqrt{E} + 1.1 \%) \oplus 1.6 /E

MC: (58.0 %/ $\sqrt{E} + 1.3 \%) \oplus 1.9 /E

data: (59.5 %/ $\sqrt{E} + 1.8 \%) \oplus 2.1 /E
Comparison with pion data

Linearity
1996 Combined Calo Test Beam
The effect of energy non-conservations

Include in each FLUKA interaction an energy non-conservation similar to the one observed in the old GEANT3-GHEISHA package as a function of projectile/energy

Simulation: Positive Pions in the ATLAS 1996 Combined Calo set-up

<table>
<thead>
<tr>
<th>E(GeV)</th>
<th>Per Interaction</th>
<th>Per Event</th>
<th>$\sigma/E$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_{\text{miss}}$</td>
<td>$E_{\text{miss}}$</td>
<td>FLUKA</td>
</tr>
<tr>
<td>10</td>
<td>0.094</td>
<td>2.1</td>
<td>24%</td>
</tr>
<tr>
<td>100</td>
<td>0.070</td>
<td>12.7</td>
<td>7.2%</td>
</tr>
</tbody>
</table>

To enforce energy and momentum conservation at each step is as important as having sound physical models!!
The background in the ATLAS hall

Computed photon (right) and neutron (left) background in the ATLAS experiment at LHC
LHC background benchmarking

Absolute yield and spectral measurements of photons and neutrons emanating from the final stages of hadronic showers have been checked with a $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ detector with 40 and 120 GeV/c beams on 11 $\lambda$ (200 cm) and 14 $\lambda$ (240 cm) thick cast iron targets.

The results were intended to verify or disproof the simulations used for assessing the soft particle background at LHC experiments (E. Gschwendtner, H. Vincke, C.W. Fabjan, N. Hessey, T. Otto, CERN-EP/2001-025, submitted to NIMA)
LHC background benchmarking

Computed shower composition at 40 GeV/c, 240 cm thickness (left), and computed event multiplicity in the BGO (right)

Showers are still dominated on axis by late π^0 !!

↓

The event multiplicity and possible accompanying charged particles must be accounted for in order to reproduce properly the experimental conditions and vetos
## LHC background benchmarking II

| Measurement set-up | Signal rate $\times 10^{-4}$ | Ratio  \\
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Simulated</td>
</tr>
<tr>
<td>$p_{\text{beam}} = 40,\text{GeV/c}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 cm on-axis</td>
<td>76.2 ± 0.4</td>
<td>71.8 $^{+6.7}_{-14.9}$</td>
</tr>
<tr>
<td>200 cm off-axis</td>
<td>6.8 ± 0.2</td>
<td>6.1 $^{+0.8}_{-0.7}$</td>
</tr>
<tr>
<td>240 cm on-axis</td>
<td>23.0 ± 0.4</td>
<td>15.8 $^{+2.7}_{-3.6}$</td>
</tr>
<tr>
<td>240 cm off-axis</td>
<td>2.3 ± 0.1</td>
<td>1.9 $^{+0.3}_{-0.2}$</td>
</tr>
<tr>
<td>$p_{\text{beam}} = 120,\text{GeV/c}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 cm off-axis</td>
<td>26.3 ± 0.4</td>
<td>26.0 $^{+3.0}_{-2.9}$</td>
</tr>
<tr>
<td>240 cm on-axis</td>
<td>93.5 ± 1.7</td>
<td>78.6 $^{+9.6}_{-11.1}$</td>
</tr>
<tr>
<td>240 cm off-axis</td>
<td>9.7 ± 0.6</td>
<td>7.8 $^{+1.4}_{-1.3}$</td>
</tr>
<tr>
<td>Weighted average</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Summary of measured and simulated signal rates in the energy interval $0.35\,\text{MeV} < E < 9\,\text{MeV}$ per incident beam particle
### LHC background benchmarking III

<table>
<thead>
<tr>
<th>Measurement set-up</th>
<th>$\langle E\text{-deposition}\rangle$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
</tr>
<tr>
<td>$p_{\text{beam}} = 40 \text{GeV/c}$</td>
<td></td>
</tr>
<tr>
<td>200 cm on-axis</td>
<td>2.045 ± 0.018</td>
</tr>
<tr>
<td>200 cm off-axis</td>
<td>1.615 ± 0.004</td>
</tr>
<tr>
<td>240 cm on-axis</td>
<td>1.923 ± 0.009</td>
</tr>
<tr>
<td>240 cm off-axis</td>
<td>1.666 ± 0.003</td>
</tr>
<tr>
<td>$p_{\text{beam}} = 120 \text{GeV/c}$</td>
<td></td>
</tr>
<tr>
<td>200 cm off-axis</td>
<td>1.572 ± 0.009</td>
</tr>
<tr>
<td>240 cm on-axis</td>
<td>2.051 ± 0.020</td>
</tr>
<tr>
<td>240 cm off-axis</td>
<td>1.649 ± 0.006</td>
</tr>
</tbody>
</table>

Summary of measured and simulated averaged energy depositions in the energy interval $0.35 \text{MeV} < E < 9 \text{MeV}$
Computed and measured total spectra for two different beam energy, thickness and position combinations.
Future developments:

- Ion interactions:
  - Consolidation and benchmarking of the interface with DPMJET
  - Extension of the present nuclear models to handle light ions in the intermediate energy range

- A new powerful and user friendly interface through the ROOT system
- Residual activity and dose rates: *Online use of databases for:*
  - *Cooldown* calculations (already implemented offline)
  - $\gamma$, $\beta$ and $\alpha$ radiation emission and transport online.

- DPM: add multi-Pomeron exchanges
- PEANUT extension to high energy
- Refinements to evaporation, inclusion of heavy fragment emission
- New low energy neutron library